DEPARTMENT OF THE ARMY   CORPS OF ENGINEERS

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

A STUDY OF SAND MOVEMENT AT SOUTH LAKE WORTH INLET FLORIDA

TECHNICAL MEMORANDUM NO. 42

A STUDY OF SAND MOVEMENT AT SOUTH LAKE WORTH INLET FLORIDA

FOREWORD

This paper presents the results of a study made at South Lake Worth Inlet, Florida, in connection with operation of a sand by-passing plant. The study was made under the parts of the Board's program concerning the relation of littoral drift to wave energy and the design of sand by-passing plants. Field work included measurement of the volume of material by-passed by the pumping plant; recording of wave height, period, and direction; measurement of alongshore currents in the nearshore zone; and procurement of sand samples. A portion of the paper was delivered at the ASCE convention at Miami Beach, Florida, in June 1953.
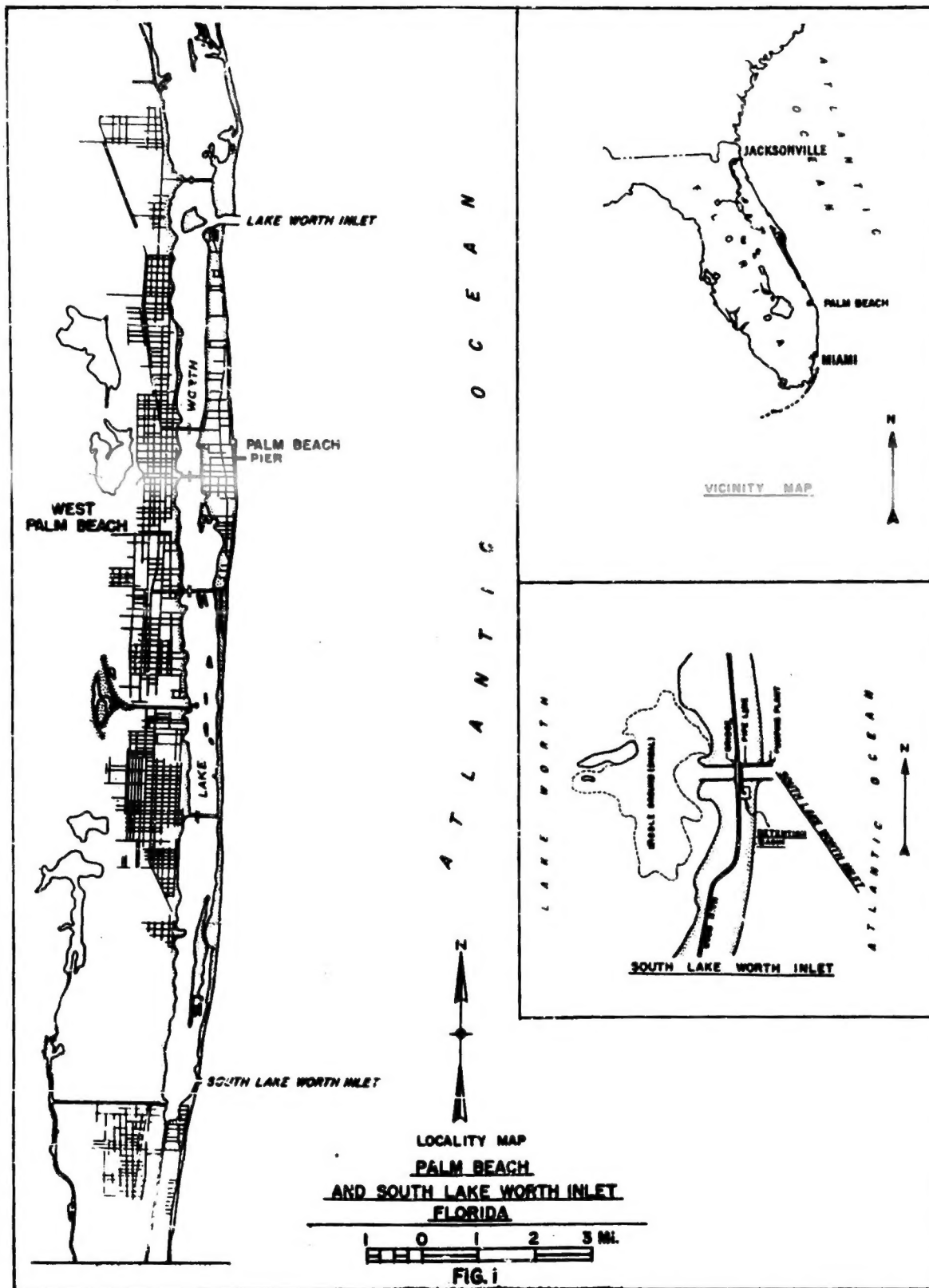
The author of the report and project engineer for this study was George M. Watts of the Research Division of the Beach Erosion Board under Joseph M. Caldwell, Chief of the Division. Field data were procured by a Field Group under the direction of George P. Magill from the Board's Engineering Division. The field data were analysed by the Research Division staff. At the time the report was completed, the technical staff of the Board was under general supervision of Colonel J. U. Allen, Resident Member and R. O. Eaton, Chief Technical Assistant. The report was edited for publication by Albert C. Rayner. Views and conclusions stated in the report are not necessarily those of the Beach Erosion Board.

Acknowledgement is made of the earnest and complete co-operation rendered to the Beach Erosion Board Field Group during the course of the study by the South Lake Worth Inlet District Commission; Mr. J. M. Boyd, County Engineer, Palm Beach County, and his staff; Mr. L. T. Lockwood, Town Manager of Palm Beach, and his staff; Mr. M. Cohen, owner of the Palm Beach Pier; and Mr. Borsten, manager of the Ambassador Hotel in Palm Beach.

TABLE OF CONTENTS

VICINITY MAP

LAKE WORTH INLET

WCVTH

PALM BEACH
PIER

WEST
PALM BEACH

LAKE

SOUTH LAKE WORTH INLET

ATLANTIC OCEAN

JACKSONVILLE

PALM BEACH

MIAMI

N

SOUTH LAKE WORTH INLET

LAKE WORTH

ATLANTIC OCEAN

N

LOCALITY MAP

PALM BEACH
AND SOUTH LAKE WORTH INLET
FLORIDA

1   0   1   2   3 MI.

FIG. i

A STUDY OF SAND MOVEMENT AT SOUTH LAKE WORTH INLET, FLORIDA

BY

George M. Watts
Hydraulic Engineer, Research Division
Beach Erosion Board, Corps of Engineers

INTRODUCTION

Purpose. The stationary sand pumping plant on the seaward end of the north jetty at South Lake Worth Inlet, Florida, was installed in 1937 as a means of intercepting the drifting sand from the north, passing the material across the inlet entrance, and depositing it on the shore south of the south jetty. This operation is intended to reduce the shoaling at the inner and outer ends of the inlet channel, and to supply sufficient material to maintain the shore south of the inlet. The plant is believed to be the first installation of its type in this country; therefore its design, and the shore processes involved have all been of considerable interest to those concerned with coastal engineering. Compilation and study of factual data associated with the plant should lead to a better understanding of the problem of by-passing sand at inlets. By a series of field measurements, attempts were made to investigate the effectiveness with which a fixed plant can pump the littoral material brought within reach of its intake by littoral forces, and to relate the volume of sand reaching the pump intake to the wave energy reaching adjacent shores.

History of Inlet and Adjacent Shores. As shown on Figure 1, Lake Worth is the lagoon separating Palm Beach from West Palm Beach, Florida. The town of Palm Beach occupies the barrier beach which separates Lake Worth from the Atlantic Ocean. Prior to 1918, Lake Worth had no direct communication with the ocean. Lake Worth Inlet, located near the northern limit of Palm Beach, was dredged and two entrance jetties constructed between 1918 and 1925. The inlet was created for commercial and pleasure craft usage.

South Lake Worth Inlet, located near the south end of Lake Worth, about 15 miles south of Lake Worth Inlet, was dredged and two entrance jetties were constructed in 1927. The primary purpose of this inlet was to create a circulation of water in the southerly end of Lake Worth, thereby alleviating a stagnant water condition. The inlet channel also permits passage of pleasure craft drawing up to 6 or 8 feet. It is about 125 feet in width and some 600 feet in length. The entrance jetties are about 250 feet long. Their top elevation is about 12 feet above mean low water.

The predominant direction of littoral drift along the Florida coast is generally from north to south. After the impounding area north of

1

the north jetty at South Lake Worth Inlet was filled, material was carried around the seaward end of that jetty into the inlet channel. Flood currents transported much of this material through the channel into Lake Worth where the material accumulated as a large shoal. On ebb tide, seaward currents in the channel transported a portion of the material to the area seaward of the jetties and created an outer bar. The material moved by ebb currents plus the littoral movement in deeper waters was then the only material which passed the inlet and reached the beach area south of the south jetty. Throughout the history of the inlet, this supply was insufficient to maintain a stable beach south thereof, consequently erosion along this section of shore line became a serious problem. Between 1932 and 1937, property owners along the eroding area constructed seawalls and groins in an effort to check the erosion; however the supply of drift was so small that the groins were ineffective in providing a beach and it appeared that the seawalls would eventually be undermined and destroyed.

History of By-Passing Plant. The concern of the South Lake Worth Inlet District over the growth of the shoaling area in Lake Worth and the erosion of the shore south of the inlet, led to a decision to install a sand by-passing plant on the north jetty of the inlet. The by-passing plant was a joint undertaking by the Inlet District and the private property owners. The plant installed in 1937 consisted basically of an 8-inch suction line, a 6-inch, 65 horsepower diesel-driven centrigugal pump, and about 1,200 feet of 6-inch discharge line. The discharge line extended from the pumping plant, across a highway bridge which spanned the inlet, and thence to the shore south of the south jetty. After 6 months of operation in 1937, a considerable amount of accretion was evident along the shore south of the inlet, a beach of about 120 feet in width having formed in front of the seawall, whereas prior to the pumping operation the high water line was essentially at the seawall face. By 1942, or at the end of 5 years, the groins which had been constructed prior to the pump installation had trapped their full capacity of sand and were completely covered in places. The rate of shoaling in Lake Worth immediately adjacent to the inlet decreased during this period of operation.

From 1942 to 1945 the by-passing plant was not operated due to fuel shortages, and within this 3-year period severe erosion again was experienced south of the inlet. The growth of the shoaling area in Lake Worth was also approaching a point where the inlet channel no longer served its primary purpose. The Inlet District and Palm Beach County accordingly decided to resume pumping operations in 1945. The effects of the resumption of pumping were similar to those experienced in 1937, but since shoaling in Lake Worth was not satisfactorily reduced, an 8-inch pump was installed in 1948.

The present pumping plant consists of an 8-inch centrifugal pump driven by a 300-horsepower diesel motor, a 10-inch intake mounted on a swinging boom of 30-foot radius with a flexible rubber sleeve at the center of the turning radius. The intake line has an auxilary jet for

2

PUMPING PLANT NEAR OUTER END OF NORTH JETTY

DISCHARGE LINE SOUTH OF SOUTH JETTY.

FIGURE 2

3

sand agitation. The swinging boom is limited to about 12 feet vertical movement. The center of the turning radius of the swinging boom is located about 30 feet from the seaward end of the north jetty and the pump is capable of digging a circular trench about 30 feet in length and 8 to 10 feet deep. Bed rock and hard pan limit the trench depth. Normally the trench is from 5 to 3 feet in depth. The pump is some 6 feet above mean sea level. The 8-inch discharge line extends to the shore south of the inlet, as had the preceding 6-inch line. The discharge line is about 24 feet above mean sea level on the bridge over the inlet, and about 16 feet above mean sea level at its discharge end. The pump is operated as littoral material accumulates within reach of the intake. Two full-time operators are employed for operation and maintenance of the plant. If relatively calm weather prevails, a pumping time of 2 to 3 hours each day is sufficient to remove all material within reach of the intake; however when storms from the northeast occur continuous pumping often does not equal the rate of accumulation in the reservoir or impounding zone, and considerable material moves around the seaward end of the north jetty into the inlet channel. Figure 2 shows the present pumping plant near the outer end of the north jetty and the discharge line south of the south jetty.

FIELD PROCEDURE AND DATA

Test Program. The field work for this study was done from February to June 1952. It consists of: (a) measurement of material pumped by the by-passing plant, (b) measurement of wave characteristics, (c) measurement of littoral currents within the surf zone, and (d) procurement of sand samples.

Measurement of Material Pumped. The material passed was measured by preparing a detention basin at the outfall of the by-passing plant and frequently surveying the accumulated material in the basin area. The basin was initially formed by levelling a rectangular area of about 75 x 100 feet, bounded on the north, east, and south sides by sand banks 5 to 6 feet high and on the west side by the seawall previously mentioned. Figure 3 shows the basin as initially prepared with the discharge pipe of the by-passing plant in the northwest corner of the basin, and also the basin when about half filled. The outlet in the southwest corner of the basin permitted essentially sediment-free water to drain into the ocean. The east bank of the basin was situated some 50 to 60 feet landward and 10 to 12 feet above the high water line. The basin had sufficient capacity for the sand pumped during periods of 50 to 60 hours. Daily surveys of the basin area were made if the daily pumping time equalled or exceeded 6 hours; otherwise surveys were generally made when pumping time of 6 hours had accumulated.

Table 1 gives the volume of material pumped by the by-passing plant from 25 February to 11 June 1952. The volume of material pumped by the

4

Detention Basin As Initially Prepared With Outfall Of
By-Passing Plant Positioned In Northwest Corner Of Basin

Detention Basin Approximately 50 % Filled

FIG. 3

5

TABLE 1 - VOLUME OF MATERIAL PUMPED

Date 1952	Time	Pumping Time (Hours)	Pumping Times into Basin (Hours)	Volume Pumped in Cu. Yds. Computed	Estimated*
Feb 25	0900-1500	6	6	445	
26	0700-0900	2			152
27	0700-1300	6	6	491	
28	0700-1200	5			
29	0700-1330	6.5	11.5	948	
Mar 1	0700-1000	3	3	256	
3	0700-1030	3.5			267
4	0700-0900	2	2	141	
6	0700-1000	3			
7	0700-0900	2	5	373	
7	1000-1400	4			
8	0700-1100	4	8	615	
8	1200-1900	7			
8	0700-0900	2	9	705	
9	0800-1400	7			
10	0700-1430	7.5			572
11	0700-1400	7			513
12	0700-1000	3			229
13	0700-0800	1			
14	0700-0800	1			
16	0700-0800	1			
17	0700-1000	3	6	476	
17	1030-1330	3			
18	0700-0900	2	5	353	
19	0700-1000	3			
21	0700-0900	2	5	328	
22	0700-0900	2			
24	0700-0800	1			
25	0700-0800	1			
27	0700-0800	1			
29	0830-0930	1			
30	0700-1300	6	12	1168	
30	1330-1800	4.5			343
31	0700-1530	8.5			648
Apr 6	0700-1100	4			305
7	0700-0830	1.5			114
7	1500-1630	1.5			
8	0700-0800	1			
8	1500-1630	1.5			
9	0930-1230	3	7	584	
9	1530-1700	1.5			
10	0630-1330	7	8.5	731	
10	1445-1615	1.5			
11	0630-1230	6	7.5	669	
12	0730-1030	3			
17	0930-1300	3.5			
17	1530-1800	2.5	9	608	
18	1200-1800	6			
19	0600-1000	4	10	757	
19	1400-1500	1			
20	0700-1030	3.5			
20	1300-1500	2			
21	0700-1000	3	9.5	660	
22	0730-1200	4.5	4.5	366	
23	0700-1100	4			305
30	0800-1000	2			
30	1500-1700	2			
May 1	0500-0730	2.5			
1	1400-1530	1.5	8	534	
2	2000-2100	1			
3	1100-1200	1			
6	0800-0900	1			
9	0930-1030	1	4	230	
12	0730-0800	0.5			
12	1530-1730	2			
13	0700-1000	3	5.5	306	
13	1500-1630	1.5			
14	0800-1100	3	4.5	298	
14	1300-1730	4	4	270	
15	1200-1700	5	8	540	
16	0730-1030	3			
20	1300-1500	2			
21	1730-1800	1			
24	0800-0900	1	4	376	
28	0730-0800	1			
29	0800-0900	1			
Jun 3	0730-0900	1.5			
4	0700-1000	3	6.5	444	
5	0700-0830	1.5			
10	1100-1230	1.5			
11	0700-0800	1	4	234	
Totals		**235.5**	**183**	**13,952**	**4,001**

Total   17,953

*Estimated volume based on average rate of pumping, computed from pumping time and measured volume as 76.2 cubic yards per hour.

6

by-passing plant was measured by periodic surveys of the basin. When the basin became filled and required releveling, the discharge of material from the pump could not be measured during the period of re-leveling. Therefore volumes were estimated for the periods when the plant was in operation but when no volumetric measurements were made. The volumes given after these times were computed by using the average pumping rate computed from the measured data. This computed average pumping rate was 76.2 cubic yards per hour. It was desirable to obtain as much measured pumping data as possible, therefore when the study was initiated, the greatest emphasis was placed on developing suitable arrangements for measuring the material discharged by the plant. The procurement of data on volumetric measurements of pumped material was started approximately 10 days before wave characteristics were recorded.

Wave Characteristics. A Type WH-1 wave gage (1)* was used to measure the wave heights and periods. This gage consists of a pressure head designed to detect pressure changes at a selected underwater location and to transmit them electrically to a recorder. Hydrographic surveys indicate that the offshore hydrography along the Palm Beach shore and southwards to South Lake Worth Inlet (approximately 10 miles) is fairly uniform, therefore it was believed that installation of the gage in a moderate water depth any place within this area would provide wave data representative of the waves reaching the shores at and near the by-passing plant. Excellent facilities for installing and operating the gage were available at the Palm Beach Pier, located 11 miles north of the inlet. The gage was installed at the seaward end of the pier on the ocean bottom in about 17 feet of water (referred to mean sea level). The re-cording mechanism was programmed to obtain a 12-minute record every 4 hours for the period from 6 March to 10 June.

The records obtained from the gage were analyzed for significant wave heights and periods(2). The results have been tabulated and plotted in Figure 4. This plot indicates the percentages of time of occurrence of wave heights or periods within the indicated value and larger. It can be noted that wave periods of 13 or more seconds occurred approximately 10 percent of the time during the period of observations. On an annual basis, these longer period waves are not common in the study area. The longer period waves were probably caused by distant northeast storms.

Wave directions were measured by the use of a sighting bar and auxiliary sights attached to an ordinary engineer's transit(3). In this method the transit is set over a point of known location and elevation, and oriented on a distant point of known direction. The sighting bar, attached to the transit, revolves in a horizontal plane approximately parallel with the sea surface and when the bar is visually aligned with a wave crest, the orthogonal azimuth is read directly on the transit. The roof of the Ambassador Hotel, approximately 3.5 miles north of the by-passing plant provided the most suitable location for an observation

*Numbers in parentheses refer to reference list on page 24.

7

Period (sec) Height (ft.)	0.0 2.9	3.0 3.9	4.0 4.9	5.0 5.9	6.0 6.9	7.0 7.9	8.0 8.9	9.0 9.9	10.0 10.9	11.0 11.9	12.0 12.9	13.0 13.9	14.0 14.9	15.0 15.9	16.0 16.9	17.0 17.9	18.0 18.9	Total Percent	Cumulative Percent
0.0-0.5	21.8																	21.8	100.0
0.6-1.0		2.7	11.3	7.2	3.9	8.4	8.2	7.9	3.0	0.4	2.9	0.7	1.4	1.1	3.6	0.6	0.9	60.4	78.4
1.1-2.0		0.2	2.3	7.2	1.8	0.9	0.9	1.8	0.5	0.5	0.7		0.2	0.2	0.2			17.2	18.0
2.1-3.0			0.2	0.2	0.4													0.8	0.8
Total Percent	21.8	2.9	14.4	14.8	7.5	2.3	8.1	8.4	4.5	0.9	3.2	0.7	2.5	1.3	3.8	0.9	0.9	100.0	
Cumulative Percent	100.0	78.2	75.3	61.0	46.5	38.0	31.7	22.6	17.2	12.9	12.0	0.8	8.0	6.4	8.8	1.4	0.9		

6 March – 10 June 1962
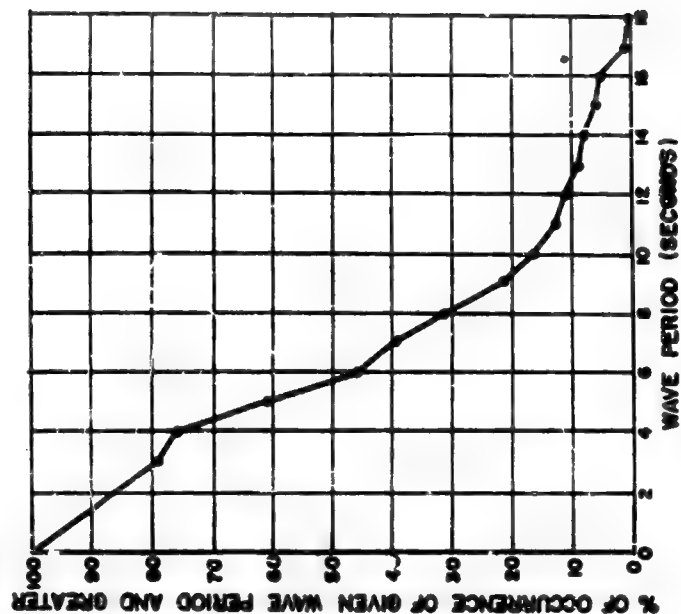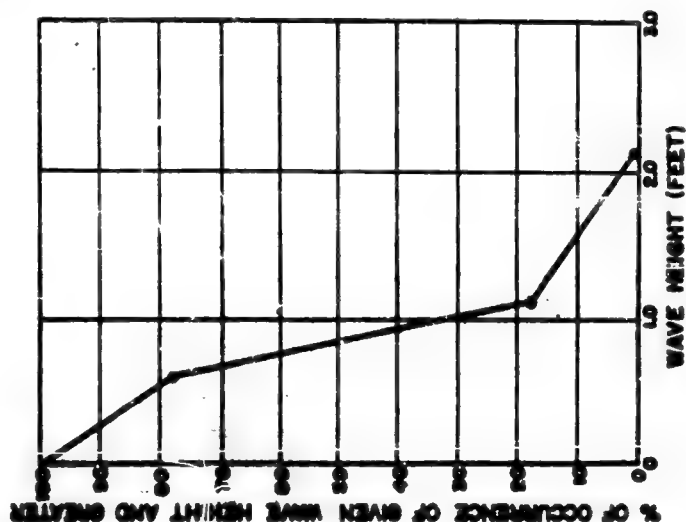
FIG. 4 WAVE HEIGHT AND PERIOD FREQUENCIES

8

6 March - 10 June 1952

Period (sec.) / Direction (azimuth) 0°-39°	0.0 2.9	3.0 3.9	4.0 4.9	5.0 5.9	6.0 6.9	7.0 7.9	8.0 8.9	9.0 9.9	10.0 10.9	11.0 11.9	12.0 12.9	13.0 13.9	14.0 14.9	15.0 15.9	16.0 16.9	17.0 17.9	18.0 18.9	Total Percent	Cumulative Percent
40°-59°	2.4		0.2	0.8	0.6	0.9	0.3	0.8	0.5		0.6							6.1	6.1
60°-79°	2.4		0.7	1.7	2.4	2.6	3.3	1.9	0.9		0.9		0.2	0.2	0.2	0.2	0.2	19.4	25.5
80°-99°	2.4	2.1	6.6	4.3	2.4	3.3	2.9	2.2	2.1	0.8	0.9	0.3	0.7	0.2	1.1	0.2	0.8	32.3	57.8
100°-119°	2.4	2.1	6.4	6.2	3.6	1.4	3.1	3.6	1.6	0.3	1.6	0.3	1.1	0.9	0.7			35.3	93.1
120°-139°	2.4	0.9	0.7				0.3	0.3	1.6	0.2	0.5							6.9	100.0
140°-179°																			

FIG. 5 WAVE DIRECTION FREQUENCIES

% OF OCCURRENCE OF STATED WAVE DIRECTION (AZ) & LESS

WAVE DIRECTION (AZIMUTH) IN DEGREES
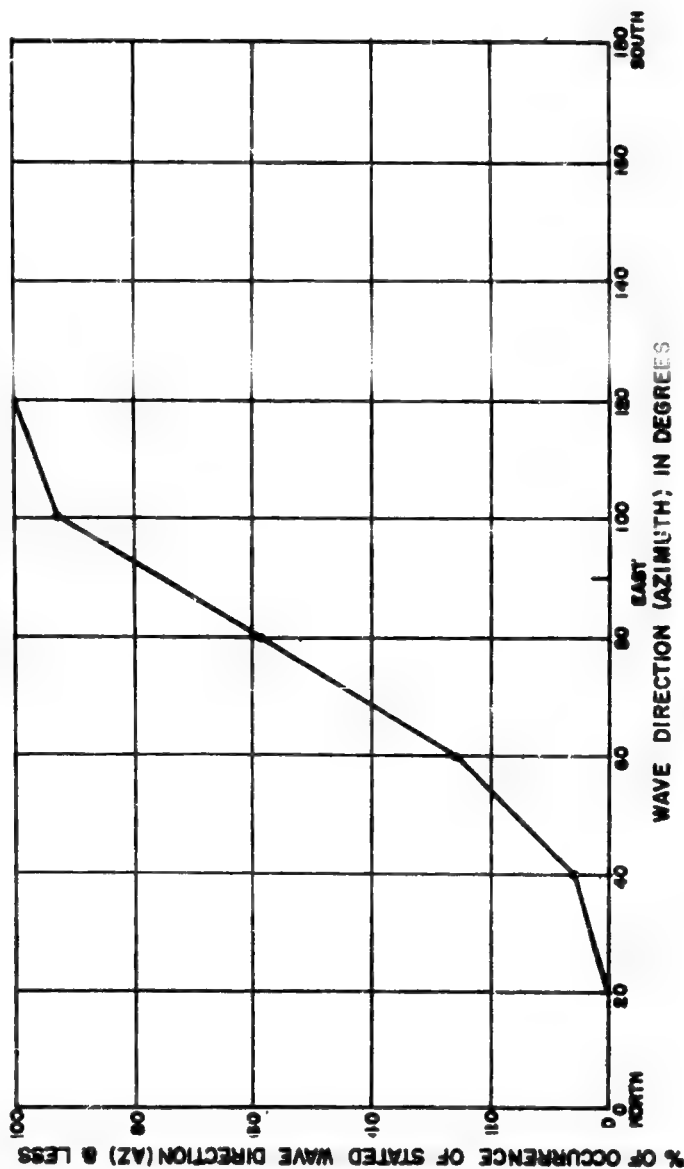
9

station in the area. The instrument was located about 300 feet landward of the shore line and 93 feet above mean sea level. Wave direction observations were obtained twice daily; once each in the early morning and late afternoon.

The wave direction observations have been tabulated and plotted in Figure 3. The wave direction was tabulated with the wave period, since the period could be determined even when the height was insufficient to be determined from the record. Figure 5 shows the percentages of time of occurrence of waves within the indicated azimuth direction and less.

Littoral Currents. Fluorescein dye was used to measure longshore currents inside the breaker zone. The method employed to measure the longshore current was to throw a small paper bag containing a handful of gravel and about two tablespoonfuls of powdered dye into the surf. The length of longshore travel of the stain during a 3-minute period, as the bag disintegrated, was measured by pacing. Four current observation stations were established north of the by-passing plant; the distances from the by-passing plant being $\frac{1}{2}$ mile, 2 miles, 5 miles, and 7 miles. Longshore current measurements were made twice daily at each station, and were taken as nearly as practicable at the same times the wave directions were observed. No attempt was made to measure any currents seaward of the breaker line. Since the material reaching the pump intake was that under the influence of the breakers, the measurement of the current landward of the breaker zone was believed to give the littoral current data pertinent to this study.

Table 2 is a summary of the littoral current observations taken at the four field observations stations. The field data for each station have been summarized by listing the number of observations of north and south littoral currents within indicated current velocity limits. The numbers of north and south littoral current observations for each velocity group are also expressed in cumulative percentages. When these values are plotted as shown in Figure 6 they show the north and south percentages of occurrence of indicated littoral current velocity or less, over the period of study.

Sand Samples. Surface sand samples were taken at the four current observation stations north of the inlet, at one station located approximately 1,000 feet south of the inlet, at the shoaling areas in Lake Worth and seaward of the inlet. Samples were taken at the high, mean, and low water lines and near the 3-foot water depth at the four current measuring stations and the station 1,000 feet south of the inlet. Five samples were taken from the shoaling areas when samples were procured from these locations. The beach samples were obtained by extracting from the surface a strip 6 to 7 inches in length, 2 inches in width, and approximately 1 inch in depth. Bottom samples were obtained with a drag sampler which basically is a tube closed at one end and with a lip attached to the other end. The tube is rigged so as to move horizontally when dragged, but to become nearly vertical when raised to the water surface. Samples

10

TABLE 2 - LITTORAL CURRENT DATA - 6 MARCH to 10 JUNE 1952

Velocity Groups (Feet Per Minute)

	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-119	120-129	130-139	140-149	150-159	160-169	Totals
0.5 Mile North of Inlet																		
No. Obs. North	8	21	18	7	9	11	9	4	4	4	1	2	0	1	0	0	0	99
Cum. %	8.1	25.3	47.5	54.6	63.7	74.8	83.9	88.0	92.0	96.0	97.0	99.0	99.0	100	100	100	10.	100
No. Obs. South	9	11	9	4	2	4	6	6	0	2	1	1	1					59
Cum. %	15.2	33.8	49.1	55.9	59.3	66.1	78.0	88.2	88.2	91.6	96.7	98.4	98.4	100	100	100	100	100
2 Miles North of Inlet																		
No. Obs. North	6	21	13	11	11	6	12	6	4	5	1	1	0	1	0	0	0	98
Cum. %	6.1	27.5	40.8	52	63.2	69.3	81.5	87.6	91.7	96.8	97.9	99	99	100	100	100	100	100
No. Obs. South	11	6	9	10	9	3	2	2	1	1	2	2	0	0	1	2	0	62
Cum. %	17.7	27.4	41.9	58	72.5	77.3	80.5	83.7	85.3	90.1	91.7	94.9	94.9	94.9	96.5	100	100	100
5 Miles North of Inlet																		
No. Obs. North	10	14	13	14	15	6	15	8	3	1	4	1	1	0	0	0	1	106
Cum. %	9.4	22.6	34.9	48.1	62.2	67.9	82.1	89.7	92.5	93.4	97.2	98.1	99	99	99	98	100	100
No. Obs. South	8	6	7	8	5	4	4	4	3	0	5	0	2	2	0	0	0	56
Cum. %	14.3	25.0	37.5	51.8	60.7	67.8	72.9	82	87.3	87.3	96.2	96.2	96.2	100	100	100	100	100
7 Miles North of Inlet																		
No. Obs. North	14	25	15	17	13	3	5	3	1	1	0	0	0	0	0	0	0	97
Cum. %	14.4	40.2	55.7	73.2	86.6	89.7	94.9	98	99.0	100	100	100	100	100	100	100	100	100
No. Obs. South	8	10	8	6	4	8	2	0	2	2	1	0	0	0	0	0	0	58
Cum. %	13.8	31.1	44.9	55.3	62.2	76.0	93.2	93.2	93.2	96.6	98.3	100	100	100	100	100	100	100
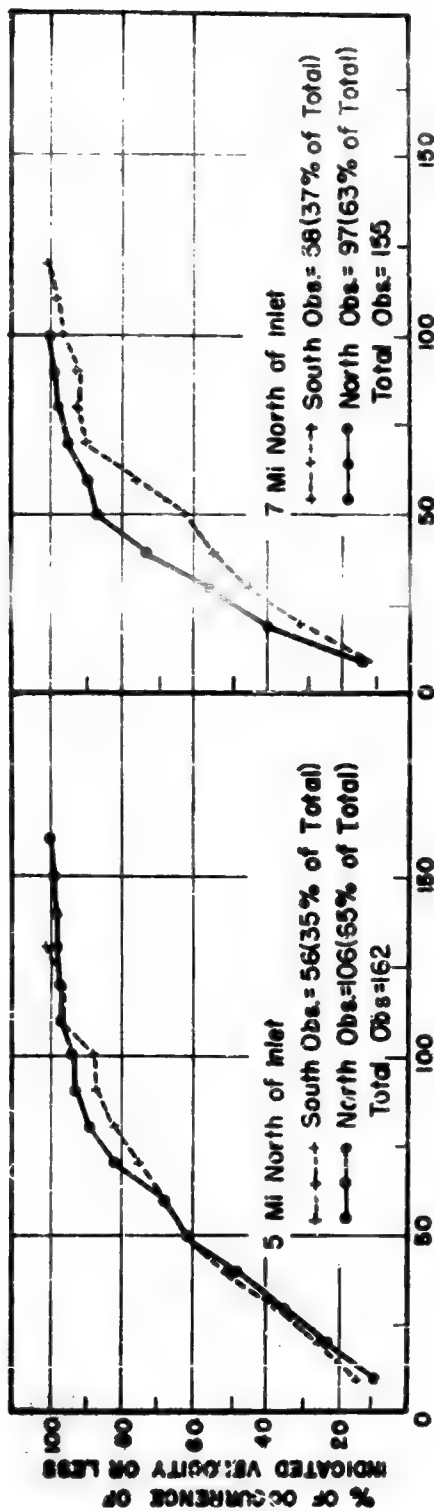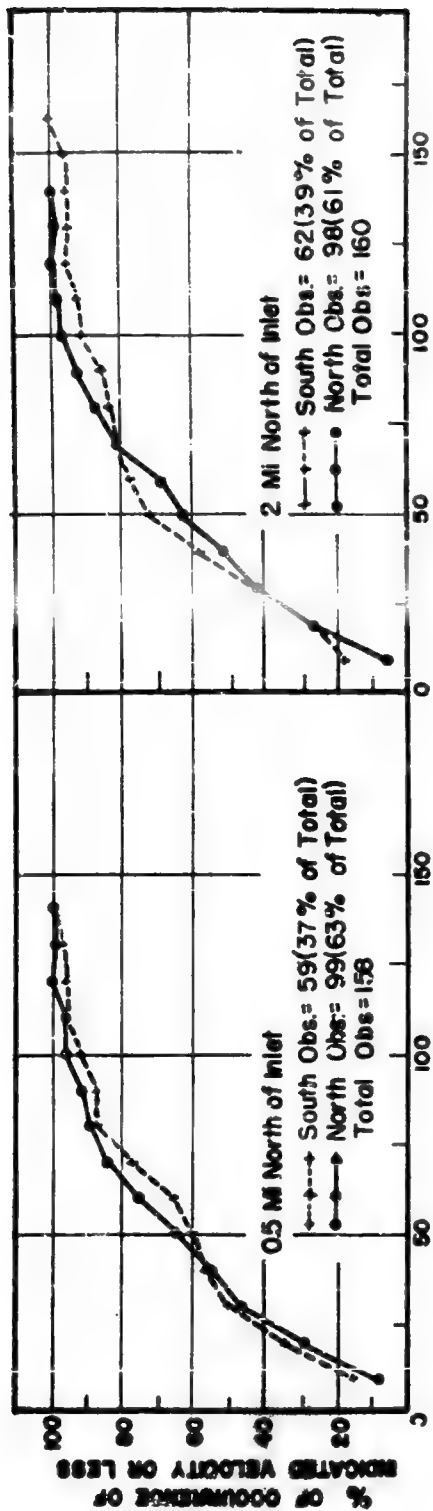
CURRENT VELOCITY FREQUENCIES

FIG. 6

12

TABLE 3 - SAND SAMPLE ANALYSIS

Dates 1952	H.T.L. Md_o (mm.)	S_o	M.T.L. Md_o (mm.)	S_o	L.T.L. Md_o (mm.)	S_o	3 ft. Water Depth Md_o (mm.)	S_o
			0.5 Mile North of Inlet					
3-7			0.37	1.24				
3-21			0.3	1.18				
4-16	0.38	1.31	0.47	1.29				
4-22	0.34	1.18			0.48	1.44	0.54	1.41
4-29			0.57	1.45			0.45	1.59
5-5	0.36	1.25	0.34	1.25	0.64	1.50	0.42	1.41
5-8	0.31	1.15	0.32	1.17	0.58	1.45	0.34	1.30
5-13	0.32	1.16	0.38	1.19	0.38	1.18	0.63	1.33
5-22	0.34	1.41	0.37	1.23	0.33	1.20		
6-10	0.29	1.18	0.36	1.29	0.53	1.55	0.33	1.29
			1000 Ft. South of Inlet					
3-7			0.68	1.23				
3-21			0.80	1.29				
4-16			0.57	1.44				
4-22			0.43	1.23				
4-29			0.71	1.27	0.47	1.31	0.90	1.24
5-5	0.50	1.17	0.61	1.28	0.63	1.09	0.77	1.34
5-8	0.43	1.29	0.52	1.25	0.74	1.25	0.88	1.16
5-15	0.53	1.22	0.40	1.14	0.48	1.36	0.54	1.38
5-22	0.45	1.23	0.58	1.23	0.86	1.18	1.01	1.12
6-10	0.50	1.25	0.66	1.32	1.02	1.15	0.92	1.29

Dates	Sample No. 1 Md_o	S_o	Sample No. 2 Md_o	S_o	Sample No. 3 Md_o	S_o	Sample No. 4 Md_o	S_o	Sample No. 5 Md_o	S_o
				Inner Bar						
3-7	0.33	1.36								
3-21	0.52	1.50								
4-22	0.47	1.81								
4-29	0.40	1.38	0.50	1.30	0.44	1.67	0.58	1.43	0.70	1.36
5-5	0.47	1.64	0.50	1.57	0.48	1.35	0.44	1.47	0.53	1.39
5-15	0.54	1.26	0.96	1.38	1.03	1.21	0.76	1.51	0.70	1.33
5-22	0.50	1.78	0.41	1.42	0.54	1.35	0.50	1.36	0.50	1.24
6-10	0.65	1.48	0.90	1.36	0.78	1.33	0.32	1.33	0.52	1.34
				Ocean Bar						
3-7	0.60	1.39								
3-21	0.60	1.28								
4-16	0.66	1.62								
4-22	0.68	1.45	0.82	1.41	0.64	1.43				
4-29	0.76	1.61	0.84	1.46	0.68	1.35	0.69	1.41	0.76	1.73
5-5	0.76	1.00	0.66	1.54	0.81	1.45	0.76	1.47	0.82	1.42
5-15	0.75	1.44	0.87	1.46	0.77	1.46	0.93	1.37	0.94	1.33
5-22	0.77	1.46	0.76	1.32	0.75	1.60	0.80	1.65	0.74	1.48
6-10	0.89	1.43	0.86	1.46	0.78	1.57	0.76	1.50	0.89	1.42

Dates	Detention Basin Md_o	S_o
3-21	0.68	1.52
4-16	0.87	1.30
4-22	1.07	1.29
5-15	1.08	1.35
5-22	0.64	1.48
6-10	0.48	1.24

H.T.L. - High tide line   M.T.L. - Mean Tide Line   L.T.L. - Low Tide line Md_o - Median diameter (mm)
S_o - Sorting Coefficient

TABLE 4 - SHELL CONTENT

Station	Shell Content in Percent by Weight				
	H.T. Line	M.T. Line	L.T. Line	3' Depth	Bars
7 Miles N of Inlet	50	36	38	50	
5 Miles N of Inlet	77	43	65	47	
2 Miles N of Inlet	60	46	67	82	
0.5 Mile N of Inlet	83	70	69	67	
1000' S of Inlet	67	67	59	88	
Ocean Bar					84
					83
					80
					76
					83
Inner Bar					51
					61
					68
					74
					70

were taken at intervals of 3 to 4 days at each location. All sand samples were analyzed for size distribution by an Emery Settling Velocity Tube(4). Table 3 lists the median diameters and sorting coefficients of typical samples taken immediately north and south of the inlet, on the bars and in the detention basin. Table 4 lists the shell content of samples.

ANALYSIS OF RESULTS

Average Pumping Rate. Referring to Table 1, the total measured volume of pumped material during this study was 13,958 cubic yards and the total pumping time to by-pass this volume was 183 hours. This indicates an average pumping rate of approximately 76.2 cubic yards per hour. When individual volume surveys and the respective pumping times are considered, the pumping rate fluctuated between approximately 50 and 100 cubic yards per hour. This indicates that the pumping rate is influenced by many factors, such as composition of material, condition of the material at the intake, the operator's manipulation of the intake, etc. In order to establish an accurate average pumping rate, many measurements over a relatively long period of time are necessary. The accuracy of the pumping rate as

established in this study cannot be quantitatively assessed. However, fairly representative pumping conditions were encountered during the course of volume measurements; this factor coupled with the number of volume measurements has, it is believed, provided a reliable average pumping rate for the present installation.

Annual Pumping Rate. The log of pumping time between January 1949 through December 1951, as furnished by the Palm Beach County Engineer, indicates the following:

Year	Total Pumping Time (Hours)	Total Volume Pumped* (Cubic Yards)
1949	1068.5	81,420
1950	1020.5	77,760
1951	1048.5	79,890

*Based on rate of 76.2 cu. yds. per hour.

Over this 3-year period the average volume pumped per year would be approximately 80,000 cubic yards, based on the average measured pumping rate. Normally the by-passing plant is operated to intercept the sand drifting southward under the influence of waves from the northeast quadrant. However, the plant is often operated when waves from the southeast quadrant prevail, since some material moves northward around the north jetty and deposits in the arc-shaped trench or sand reservoir at the pumping plant. This means that the indicated average volume of material pumped per year (80,000 cubic yards) cannot be considered entirely as southward drifting sand. No quantitative data are available that will accurately assess the yearly volume of material pumped when waves from the southeast quadrant prevailed. Waves from this sector are common during the summer months and if the time between 15 June to 15 September be assumed as an interval when all wave action is from the southeast quadrant, the average volume of material pumped during this interval is about 7,800 cubic yards or about 10 percent of the total volume. This would indicate that of the yearly volume of southerly littoral drift, the pumping plant intercepts and by-passes approximately 72,000 cubic yards.

Relation of Volume Pumped to Total Southward Drift. Accurate quantitative figures for the rate of littoral drift along the South Lake Worth Inlet area cannot be made, however estimates(5) have been made for the Lake Worth Inlet area which is some 15 miles to the north. There the effective depth of the littoral barrier (north jetty) is 27 feet as contrasted to 6 feet at South Lake Worth Inlet. The estimates were made from historical surveys of the impounding area north of the north jetty at Lake Worth Inlet, and although the surveys were inadequate to provide an accurate estimate, they indicate the range between the limits of which the true value probably lies. They indicate that during the 14-year period immediately following completion of the inlet and jetties, material was impounded at a rate averaging 150,000 to 225,000 cubic yards per year,

15

and that during the next seven years, after the impounding capacity of the north jetty had been almost exhausted, the rate was approximately 130,000 cubic yards per year. Other records(6) indicate that the shoaling area in Lake Worth at South Lake Worth Inlet gained an average of 165,000 cubic yards per year during the period 1931-1937, prior to operation of the by-passing plant. As previously stated, wave action from the southeast is common during the summer months; therefore the source of material supply for shoaling in Lake Worth is from both northward and southward littoral drift. However, exposure and shore alignment are so nearly the same at both localities, there is no reason to suspect that the drift rate is not approximately the same at both inlets. If 200,000 cubic yards per year is accepted as a normal rate of southward drift at South Lake Worth Inlet (to 27-foot depth), then the volume intercepted by the pumping plant (72,000 cubic yards) is 36 percent of this drift. It must be assumed that the littoral drift in the nearshore zone in excess of the pump's capacity plus the deep water drift (between the 6 and 27-foot depth) is on the order of 130,000 cubic yards per year. This latter figure would then be the total combined rate of material naturally by-passing the inlet and that being deposited as shoals both on the outer bar and within the inlet.

Relation of Volume Pumped to Wave Energy. The measured wave data can be expressed as wave energy (direction included) by applying accepted wave theory. It is then possible to express the measured fraction of littoral drift as a function of wave energy. As a general basis of definition, waves in water having a depth greater than one-half the wave length are considered deep water waves, and waves in lesser depths are shallow water waves. In all deep water (denoted by subscript o) wave phenomena, the relationship between wave length L_o, wave velocity C_o, and wave period T, is

$$L_o = C_o T \tag{1}$$

If constant depth d_o, is assumed and the wave height is small as compared with d_o and L_o then

$$C_o = \sqrt{\frac{g L_o}{2\pi} \ \tanh 2\pi \ \frac{d_o}{L_o}} \tag{2}$$

and as d_o becomes large, $\tanh 2\pi \, d_o/L_o$ approaches unity, which reduces the expression to

$$C_o = \sqrt{\frac{g L_o}{2\pi}} \tag{3}$$

where g is the acceleration due to gravity. Combining equations (1) and (3) gives

$$C_o = 5.12 \ T \tag{4}$$

and $\qquad L_o = 5.12 \ T^2 \tag{5}$

The total deep water wave energy, E_0, including kinetic and potential for a unit length of crest is

$$E_0 = w \ \frac{L_0 \ h_0^2}{8} \left[1 - 4\pi^2 \frac{h_0^2}{L_0^2} \right] \tag{6}$$

where h_0 is the wave height from trough to crest and w is the specific weight of the water.

The recorded wave data indicate that nearly all water depth — wave length ratios were less than one-half; therefore the energy data can be computed on the basis of shallow water wave theory. The shallow water wave (denoted by subscript $_s$) energy expression is

$$E_s = w \frac{L_s \ h_s^2}{8} \left[1 - M \ \frac{h_s^2}{L_s^2} \right] \tag{7}$$

where M is a function of d_s/L_s. As d_s/L_s increases, equations (6) and (7) approach equality and are identical when $d_s/L_s = 0.5$. For this study comparatively small wave heights prevailed, and the quantity $\left[1 - M(h_s^2/L_s^2) \right]$ in equation (7) could be considered as unity for all practical purposes. The shallow water energy expression then reduces to

$$E_s = w \ \frac{L_s \ h_s^2}{8} \tag{8}$$

For shallow water waves

$$L_s = 5.12 \ T^2 \ \tanh 2\pi \frac{d_s}{L_s} \tag{9}$$

and substituting equation (9) in equation (8), the total energy becomes

$$E_s = \frac{w}{8} \left(5.12 \ T^2 \ \tanh 2\pi \frac{d_s}{L_s} \right) h_s^2 \tag{10}$$

The irrotational wave theory (7) states that only a part of this total wave energy travels forward with the wave form and dissipates itself on the beach. The fraction n, to be applied to E_s in equation (10) is

$$n = \frac{1}{2} \left[1 + \frac{4\pi d_s/L_s}{\sinh 4\pi d_s/L_s} \right] \tag{11}$$

By letting $w = 64$ (specific weight of sea water) and introducing the fraction n, the wave energy or actual wave work in shallow water is

$$E_s = 41 \ T^2 \ h_s^2 \ n \ \tanh 2\pi \frac{d_s}{L_s} \tag{12}$$

17

The total wave work of any wave train of a given height and period in shallow water is

$$E_T = \left[\frac{41\ T^2\ h_s^2\ n\ \tanh 2\pi \frac{d_s}{L_s}}{T}\right] \qquad (13)$$

or $\qquad E_T = \left(41\ T\ h_s^2\ n\ \tanh 2\pi \frac{d_s}{L_s}\right) t \qquad (14)$

where t is the total duration of the wave train being considered and expressed in seconds, if T is expressed in seconds. The alongshore component of wave energy is a function of the angle α that the normal of the wave crest makes with the shore line. By vector analysis the alongshore component of wave energy is more accurately expressed as a function of (sin α cos α). The total alongshore component of wave energy or wave work for any wave train of a given height and period in shallow water is then

$$E_T = (41\ T\ h_s^2\ n\ \tanh 2\pi \frac{d_s}{L_s})\ t\ \sin\alpha\cos\alpha \qquad (15)$$

In order to relate equation (15) to the measured volume of by-passed material, only the southerly component of wave work was considered. It can be seen from Figure 5 that of the total number of wave direction observations, 75 percent indicate a wave direction (α) north of east. Equation (15) was evaluated for each month by tabulating wave directions where α was 90 degrees or less along with the corresponding durations for each α and recorded wave height and period data. Since for this compilation E_T is the total monthly southerly component of wave work, the measured volume of by-passed material was evaluated in terms of the total monthly southerly littoral drift. Records for the present by-passing installation indicate that about 45 percent of the normal yearly operation time falls between 1 November and 1 February and it is during this 3-month period that considerable material is carried around the north jetty of the inlet. During the period 1 March to 1 June the normal operating time is about 20 percent of the normal yearly total and during the time of this field study it appeared that, with very few exceptions the pumping plant by-passed all the littoral drift moving alongshore in the surf zone. Therefore in compiling the by-passed material for each month (during the field study) in relation to α and t, it is assumed that the pumped volume represents the total southerly littoral drift in the nearshore zone. Table 5 presents the data on a monthly and daily basis of E_T the southerly component of wave work (expressed in ft.-lbs. per day per ft. of wave crest), and the southerly rate of littoral drift (expressed in cubic yards per day). When the tabulated values are plotted on a monthly basis as shown in Figure 7, it can be seen that a relationship exists between the southerly component of wave energy and nearshore littoral drift. The data computed on a daily basis are also shown in Figure 7. It will be noted

18

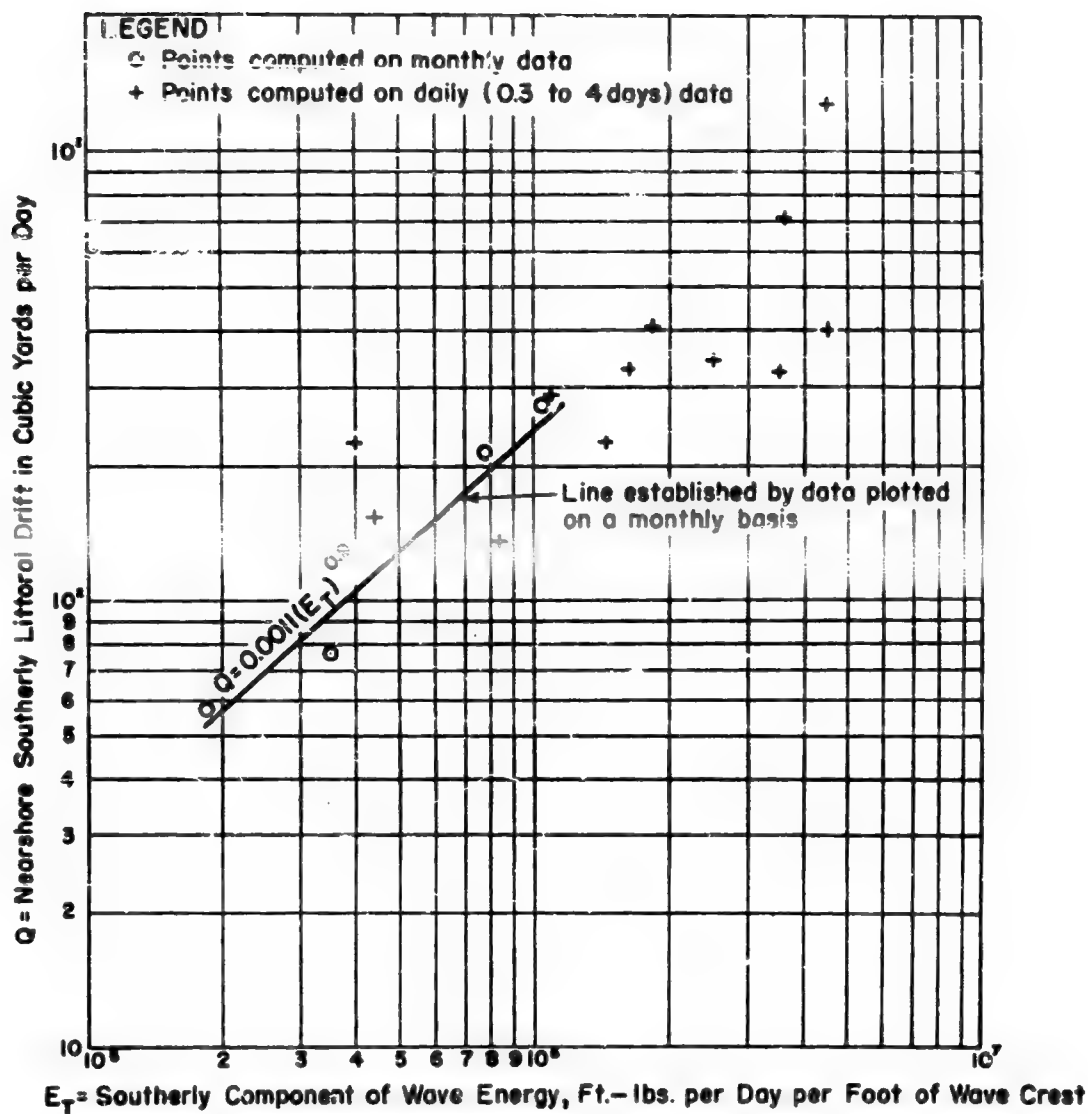## TABLE 5 - WAVE ENERGY AND LITTORAL DRIFT

Dates 1952	Net Time (Days)	Wave Energy Ft-lbs./ft. of Wave Crest for Periods Indicated x10^6	Energy (E_T) Ft-lbs/day/ Ft. of Wave Crest x10^3	Material Pumped for Periods Indicated (cu. yds.)	Nearshore Littoral Drift (Q) (Cu. yds./day)
Computations Based on Monthly Data					
Mar 7 to 31	24.23	25.26	1040	6600	272
Apr 5 to 30	25.17	19.67	780	5400	215
May 1 to 31	30.83	10.90	350	2360	76.5
June 2 to 11	9.17	1.70	185	526	57
Computations Based on Daily (0.3 to 4 Days) Data					
Mar 7 to 9	2.17	7.87	3620	1550	715
16 to 18	2	7.13	3560	657	328
28 to 30	2.17	3.94	1820	874	402
30 to 31	0.5	2.25	4500	648	1296
Apr 7 to 8	1.33	1.48	1110	380	285
16 to 19	3.17	14.45	4560	1290	406
Apr 30 to May 2	2	5.07	2535	686	343
May 12 to 16	4.17	6.76	1620	1374	330
27 to 28	0.5	0.22	440	76	152
28 to 28	0.33	0.48	1440	76	228
29 to 30	0.5	0.20	400	114	228
June 2 to 3	1.66	1.40	840	228	137

19

LEGEND
- ○ Points computed on monthly data
- + Points computed on daily (0.3 to 4 days) data

Line established by data plotted on a monthly basis

$Q = 0.0011 (E_T)^{0.90}$

Q = Nearshore Southerly Littoral Drift in Cubic Yards per Day

E_T = Southerly Component of Wave Energy, Ft.—lbs. per Day per Foot of Wave Crest

Fig. 7 RELATIONSHIP OF LITTORAL DRIFT
TO WAVE ENERGY

20

that the latter points are somewhat scattered as compared to the points computed on a monthly basis, the spread in the points being due in part to inability to associate the quantity of by-passed material with the proper wave energies. When longer time intervals are considered, as in the monthly data, the quantity of by-passed material and wave energies can be more accurately related. According to the line established on the basis of the monthly data, the relationship between Q, the nearshore littoral drift in cubic yards per day and E_T, the southerly component of wave energy for the South Lake Worth Inlet area (March through May) is

$$Q = 0.0011 \ (E_T)^{0.9} \tag{16}$$

This indicates that the rate of the measured fraction of littoral movement during the period of study was essentially a linear function of the along-shore component of wave energy.

Littoral Current Data. The plot in Figure 6 indicates that during the study the average littoral current velocity in the nearshore zone at the four observation stations was approximately 35 feet per minute. This average seems applicable to either northerly or southerly direction of current movement.

The wave direction summary (Figure 5) indicated that during the period of this study the predominant wave direction was from the northeast quadrant. The tabulated littoral current observations (Table 2) indicate that of the total number of observations, 63 percent were of movements towards the north. All other data throughout the course of this study provide evidence that the predominant direction of sand movement was towards the south. The lack of correlation between littoral current and wave directions is probably due to the insufficient number of current observations. It was found in a number of cases that littoral current measurements taken at one observation station differed in alongshore direction (north or south) and magnitude from those taken at an adjacent observation station at approximately the same time. The near coast circulatory currents created by the flow of the Gulf Stream and the Gulf Stream's effect on incoming waves are undoubtedly influencing factors on the littoral current characteristics; however these effects cannot be evaluated with the data at hand.

Sand Sample Data. Table 3 contains data on sand samples taken near the inlet. The table includes the date, sampling station, specific location on the beach profile, median diameter, and sorting coefficient, which is the square root of the ratio of the size at the 25 percent quartile to the size at the 75 percent quartile. Bottom samples from the shoaling areas inside and outside of the inlet were taken from various points on the bars; the water depth at the sampling points being 1 to 3 feet referred to mean low water datum. The samples taken from the accumulated material in the detention basin were selected at points which were believed to be representative of the by-passed material, i.e., the sorting effect created by the wash of the discharge was considered.

21

In comparing the analyses of the sand samples taken ½ mile north and 1,000 feet south of the inlet, it will be seen that the sorting coefficient (Table 3) and shell content (Table 4) at these locations are about the same; however the median diameters of the samples taken south of the inlet are noticeably larger. Considering the overall length of study, there seems to be no seasonal effects on the size distribution of the material. The average median diameters at the two stations were as follows:

Station	Median Diameters in Millimeters			
	(H.T.L.)	(M.T.L.)	(L.T.L.)	(3 ft. depth)
½ mile north of inlet	0.33	0.39	0.50	0.45
1,000 feet south of inlet	0.49	0.58	0.70	0.84

The coarseness of the material on the ocean and inner bars is indicated by the respective average median diameters of 0.77 and 0.60 millimeter. The material pumped also was coarse, samples from the retention basin having an average median diameter of 0.8 millimeter.

The transportation of sediment through and around the inlet is complex. The source of supply of material carried through the inlet to Lake Worth on flood tide could be material from the Ocean bar, material in deeper waters seaward of the jetties, and material that moves around the seaward ends of the jetties during severe wave action periods. The material carried through the inlet into Lake Worth on flood flow deposits in a fan shape pattern with the finer particles being carried into deeper waters in Lake Worth; undoubtly a substantial quantity of the finer particles remain in the deep water in Lake Worth and are not disturbed during ebb flow. However, the finer particles deposited in the immediate vicinity of the inlet are picked up on ebb flow and transported back to the ocean. This leaves a residual deposition just inside of the inlet of fairly coarse material which is shown by the bottom samples taken in that zone (average Md_0 = 0.60 mm). The finer particles transported from Lake Worth to the ocean during ebb flow either deposit on the ocean bar or are carried out into deeper waters. It seems that little fine material remains on the ocean bar, since the bottom samples taken from that zone indicate a rather coarse residual (average Md_0 = 0.77 mm.). This rather complex sediment transportation pattern seems to indicate that only the coarser material is available to the shore line immediately south of the inlet as a result of natural movement.

Since the north jetty, in order to impound material, must establish a steeper-than-normal nearshore slope, it is logical to assume that the by-passing material is a segregated coarser fraction of the material in transit. Also the trench at the intake of the by-passing plant is a natural trap for the coarser fraction of the material in transit. If

this coarser material were not by-passed mechanically, it is probable that a large part of it would deposit in the inlet and on the inner and outer bars. Although it could be expected that the inlet would ultimately either close or stabilize so that all littoral material would pass it naturally, it is evident that the downdrift shore would be under-nourished with respect to coarse material for a lengthy period, if by-passing should be discontinued. There are no data available concerning offshore conditions south of the inlet. Stability of the shore as a result of by-passing over an extended period indicates that for the conditions of limited depth which prevail at this inlet, only the coarser fraction need be by-passed to achieve satisfactory results.

SUMMARY

Effectiveness of Plant. The average pumping rate of the plant, as determined by volumetric measurements of the material by-passed during this study, is 76 cubic yards per hour. When this pumping rate is applied to an average yearly operation, the total by-passed volume of southward littoral drift is approximately 70,000 cubic yards, or 35 per-cent of the total southward drift which is on the order of 200,000 cubic yards. The by-passed material is apparently the main source of supply to the shore immediately south of the inlet.

The coarser composition of beach material on the ocean and inner bars, on the beach south of the inlet, and in the detention basin, as compared with that on the beach north of the inlet, indicates that only the coarser fraction reaches the shore to the south, by either natural processes or pumping. This fact probably accounts for the demonstrated effectiveness of the by-passing operation in stabilizing the shore south of the inlet by pumping only about one-third of the total volume of littoral drift.

Littoral Drift - Wave Energy Relation. By correlating the data on material pumped and wave characteristics over the period of study, the following relationship between the rate of nearshore littoral movement and the shallow water wave energy was developed:

$$Q = 0.0011 \ (E_T)^{0.9}$$

Q is the southerly rate of nearshore littoral drift in cubic yards per day and E_T is the southward component of wave work or energy for the corresponding period. So far as is known, this relationship is only applicable under the conditions presently existing in the vicinity of the study area. No quantitative assessment of the accuracy of this re-lationship over a longer period can be made with available data; however, the data exhibit a logical and systematic trend, and if the energy could be evaluated on an annual basis, it would be reasonable to expect the relationship to be applicable over that period.

REFERENCES

(1) Beach Erosion Board Bulletin, Volume 6, No. 4, October 1952

(2) Procedure for Interpreting Pressure Records of Swell, R. E. Folsom, HE-116-56, 14 February 1945, University of California, Berkeley, California.

(3) Beach Erosion Board Bulletin, Volume 4, No. 2, April 1950.

(4) Emery, K. O., Rapid Method of Mechanical Analysis of Sands, Jour. Sed. Petrology, Volume 8, No. 3, p. 109-111, 1938.

(5) Corps of Engineers, Department of the Army (1948). Palm Beach, Florida. Beach Erosion Study; House of Representatives Document No. 772, 80th Congress, 2d session.

(6) By-Passing Sand at South Lake Worth Inlet, Florida, J. M. Caldwell, Proceedings of First Coastal Engineering Conference, October 1950, Council on Wave Research, University of California, Berkeley, California.

(7) Breakers and Surf, Principles in Forecasting, H. O. No. 234, Hydrographic Office, U. S. Navy Department.